Clearing the Path to Transcend Barriers to Walking: Analysis of Associations between Perceptions and Walking Behaviour

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Abstract

Walkability is much studied, but the relative importance of perceptions and motivations is still not consensual. This study took a holistic approach to examine the comparative importance of a range of possible perceptions, motivations and individual characteristics on walking levels.

Data from Auckland Transport's Active Modes online survey (AT survey, N= 4,114) captured environmental perceptions and travel behaviour. Machine learning (gradient boosting) was used to predict walking levels from perceptual data and individual characteristics and determine the relative importance of each variable. Strong predictors of walking included the use of public transport, walking perceived as saving money and avoiding parking hassle, age group, and overall satisfaction with walking. Surprisingly, the importance of expected dimensions such as perceived availability of destinations or internal motivations was null in the general model.

These findings suggest a more holistic view of walking behaviour is needed, one that moves beyond the pure availability of destinations.

1. Introduction

In response to major threats such as climate change, exclusion, or sedentary lifestyle-related illnesses, cities are increasingly focused on liveability, health, or equality of access (C40 Cities, 2018; Glazener & Khreis, 2019; UN-HABITAT, 2014, 2016; World Health Organization, n.d.). Everyday walking is gaining traction globally as a policy goal (Auckland Council, 2018b; Giles-Corti, 2017; Lowe et al., 2015; UN DESA, 2016; UN-HABITAT, 2014, 2016), given its contributions to equity of access (Burdett, 2018; Gibson et al., 2012; NZIER, 2014; Rose et al., 2009), participation (Bigonnesse et al., 2018; Eisenberg et al., 2017; Fomiatti et al., 2014; Hoenig et al., 2003; Mindell, 2017), physical activity (Alidoust & Bosman, 2015; Annear et al., 2014; Badland, 2007; Eisenberg et al., 2017; Haselwandter et al., 2015; Webber et al., 2019), urban economic efficiency (Davis & Golly, 2017; P. McCann, 2009), and lower greenhouse gas emissions (C40 Cities, 2018; United Nations, 2015). The potential of retrofit and better urban design for encouraging and enabling walking are now well understood (Gehl, 2010; Gunn et al., 2017; Macmillan et al., 2020; Speck, 2012). The question authorities around the world battle with is *how* to improve urban environments to make the biggest difference, bearing in mind pragmatics such as economic and time constraints (Burdett, 2018; The Landscape Architecture Foundation (LAF), 2016; UN-HABITAT, 2016).

Walkability research has made important progress in understanding walking behaviour and barriers to walking. It is now widely accepted that walking is simultaneously influenced by the urban environment (UE) – encompassing buildings, greenery, and traffic, but also by individual, organisational or community factors (socio-ecological framework) (Alfonzo, 2005; Forsyth, 2015; Sallis, 2009; Sallis et al., 2016). There is, however, no consensus on the *relative* importance of diverse UE characteristics on walking (Alfonzo, 2005; Badland, 2007; Forsyth, 2015; Franckx, 2017; Kerr et al., 2016; McCormack & Shiell, 2011). Promising theoretical developments and some testing has been done (Alfonzo, 2005; Buckley et al., 2016; Mehta, 2008). While it is unclear if a unique and robust model for understanding walking behaviour exists, it is important to also understand what is *not* walkable and might shift people to use another mode or avoid trips within walking distance (Alfonzo, 2005; Buckley et al., 2016; Forsyth, 2015).

A recent systematic umbrella review examined the development of the conceptual framework linking the built environment and walking behaviours (Bozovic et al., 2020). Briefly, the Social Model of Walkability posits that the relationship between the UE and an individual's walking behaviour is moderated conjointly by (1) people's perceptions of their environment (namely their perceptions of the satisfaction of their walking needs: how feasible, accessible, safe, comfortable or pleasant a trip is); (2) individual characteristics (e.g. disability[1], constraints, preferences or available alternatives); (3) trip purpose, and (4) internal motivations. The review concluded that little attention has been given to environmental perceptions in both research and in the modernist approaches to urban design and transport planning.

This study builds on the findings of the realised umbrella review(Bozovic et al., 2020), exploring the associations between perceptions, individual characteristics and walking behaviour. This exploration considers Tamaki Makaurau-Auckland, Aotearoa-New Zealand, a city of 1.66 million residents (2018) (Auckland Council, 2018a). Auckland's transport infrastructure and low density are comparable to those of other car-oriented cities (Peter Nunns, 2014).

Auckland Transport is the agency charged with urban transport planning and operations. Data from Auckland Transport's Active Modes online survey (AT survey) were used. The AT survey aims to understand behaviours, attitudes and perceptions of different modes of travel, over time(TRA, 2017), capturing perceptions of the walking environments, as well as a vast array of possible motivators and deterrents, and travel behaviour.

[1] For the ease of reading, the notion of "walking" further fully encompasses wheelchair use, crutches and other mobility devices.

The aim of this study is to compare the importance of (1) perceptions of the walking environments and namely those perceptions relative to the satisfaction of the walking needs; (2) public transport use and (3) individual characteristics in the prediction of walking levels. The individual variables used as inputs all relate conceptually to walking, however the novelty of the present approach is to consider them simultaneously against the walking behaviour. The assumption is that all three aspects play a role in predicting walking levels, the focus being on their relative importance.

2. Methodology

2. 1 Setting and data

Auckland's development has had a strong focus on traffic infrastructure and urban sprawl (Auckland Council, 2018b; Gehl Architects, 2010). Jan Gehl saw a fantastic location and natural environments but described the city as "a rush hour 'traffic machine'", referring to a car-centric design (Gehl Architects, 2010). The car-centric design contributes to the high rates of pedestrian deaths and serious injuries (Howard, 2018), social isolation (Rose et al., 2009), reduced affordability for the end users of transport systems and the communities (Mattingly & Morrissey, 2014; B. McCann et al., 2000), loss of economic productivity (Davis & Golly, 2017; P. McCann, 2009), difficulties of access and low walking levels (Auckland Council, 1999, 2018b; Auckland Council Strategic Advice Unit, 2018). Adults walk about 450m (6 minutes) on average per day (Ministry of Transport, 2017) and 17% of trip legs(NZ Ministry of Transport, 2015), versus for instance 25 to 28% of all trips for the cities of London (Mayor of London & Transport for London, 2019), Vancouver (City of Vancouver, 2017) or Vienna (City of Vienna, 2015). Walking is often perceived as complicated or stressful (Ministry of Transport, Transport Knowledge Hub, n.d.; TRA, 2016). For non-disabled people, identified deterrents include environments that people perceive as unpleasant (e.g. car-dominated environments) (Bean et al., 2008; Gehl Architects, 2010), or dangerous regarding traffic and crime (Auckland Council, 2016b; Bean et al., 2008; Houghton et al., 2017; Ministry of Transport & Auckland Council, 2018). For the disabled people, evidence indicates acute barriers to access (Auckland

Disability Research Group, 2009), similarly to the situation across New Zealand (Brennan, 2016; Human Rights Commission, 2005; NZ Transport Agency, 2018).

The systemic issues experienced in Auckland are similar to those experienced in other post-industrialised cities (Fry, 2017; Gehl, 2011; Jacobs, 1961; Miller et al., 1966; The Landscape Architecture Foundation (LAF), 2016). However, potentials exist, as a quarter of car trips are shorter than 1 km(Ministry of Transport, 2017), and walking is perceived as an important activity (Bean et al., 2008). Like many other cities in the global North, Auckland aspires to safer streets and a shift in people’s preferences towards walking and public transport (Auckland Council, 1999, 2016a, 2018b; Healthy Auckland Together, 2017; Ministry of Transport & Auckland Council, 2018). Auckland therefore constitutes an interesting environment for studying how to improve conditions for walking in car-dominated environments.

The Auckland Transport's Active Modes online survey (AT survey) survey is conducted on an annual basis. The complete survey methods are provided elsewhere (TRA, 2018). Briefly, participants are contacted by an independent organisation through email invitations. Representativeness is sought by age, gender, and neighbourhood of residence.

In this study, data collected between 2016 and 2018 (inclusive, N=4,114) were examined. The authorisation to analyse the data was received from Auckland Transport, provided aggregate results were presented. Table 1 shows the characteristics of the dataset relative to the total Auckland population.

Table 1: Overview of the survey population vs. total Auckland population

Data category	N	N%	Total Auckland population
Participants (aged >14 years)	4,114		1.26 m [a, b]
… with difficulties walking	398	9.7	13% (Statistics New Zealand, 2014) [c]
… aged >18 years	3,996	97.1	95% [a, d]
… aged >65years	317	13	15% [a]
Number of trips made [e]	92,071		

… walked	23,814	26
… driven	52,616	57

[a] Census 2018, http://nzdotstat.stats.govt.nz; [b] 0.33% of Auckland's 2018 population aged 15+; [c] The NZ 2018 Census data on disability types and levels for Auckland are not available at this stage (July 2020). Data from the 2013 Disability survey are noted for reference; [d] Auckland: proportion relative to the population aged above 15, for comparability with the survey data; [e] Survey: trips made in the previous week; 3.2 trips per person per day. These cannot be directly compared with the total trips made in Auckland as the survey methods differ. The driving age limit is 16, therefore the 25 participants aged 15 were not drivers.

2. 2 Survey questions

The 2018 survey included 28 questions on cycling and 16 on walking. Questions of specific interest for this study include: (1) walking behaviour – number of trips for transport in the previous week, walked or done by other modes, by purpose; (2) attitudes to walking and overall satisfaction; (3) perceptions of the walking environment: perceived safety and agreement/disagreement with 14 possible deterrents to walking; (4) internal motivations for walking (potential motivations presented with options to agree or disagree); as well as individual characteristics. The ten survey questions that were examined in relation to the points above are presented in Supplementary file A, and a few examples are presented below for illustration.

Table 2: Subsample of survey questions, for illustration (see supplementary file A for the full list)

Code	Question	Possible answers
S7_1	Do you have any disability or impairment that affects your ability to walk?	y/n
Q10	From the list below, what are the key reasons you choose to walk? Please select all that apply ▪ There's no other way to get where I need to go ▪ Keeps me fit / helps me get fitter ▪ It's fun ▪ Saves money ▪ Saves time ▪ More consistent travel time ▪ Avoids parking hassles ▪ Availability of paths / walking routes ▪ Helps reduce traffic congestion ▪ Helps address environmental concerns ▪ Provides me with some 'me time' ▪ Allows me to enjoy the weather ▪ Better routes are available than previously ▪ Other (please specify)	y/n for each possible motivator
B8	Which of the following statements best describes you when it comes to walking, and the amount of walking you do?	Please select one only I only walk if I have to I would like to walk less

Code	Question	Possible answers
		I am happy with the amount of walking I do I would like to walk more

Most variables were dichotomous (yes/no), while for some, participants were asked to give a rating between 0 and 10 (for instance, for the question B14, about the perceived safety, 0 corresponds to "Not at all safe" and 10 to "Extremely safe"). The ten considered survey questions correspond to a total of 41 variables: for instance, the question Q10, “From the list below, what are the key reasons you choose to walk? Please select all that apply”, offers 14 possible items, responded yes or no. Each item is considered as one variable. Two limitations should be noted: (1) "walking" doesn't include using a wheelchair; and (2) respondents with "any disability or impairment (affecting their ability to walk)” or those who don’t walk at least monthly were not asked about walking/wheeling behaviour and barriers.

2. 3 Data preparation and analysis

Prior to analysis, participants were excluded if they reported difficulties walking or declared walking ‘never’ or ‘almost never’, as these individuals were not asked questions about their perceptions of the environment or their motivations. An upper threshold of 30 trips walked was set, excluding 2.9% of observations (103 observations) which were likely data entry errors (for instance, one participant noted 486 trips walked in a week). Next, walking was dichotomised into “low” and “high” levels of walking by first splitting the data into tertiles and retaining the first and third tertiles. The first tertile corresponds to 0 trips walked in the previous week (n=1343, 39% of the sample), while the third tertile corresponds to five or more walking trips in the previous week (n=1223, 35%). This split was chosen to maximise the heterogeneity between groups: those who didn’t walk, and those who walk on most days of the week. This meant that 3,456 of the initial 4,114 participants were included in the analysis.

First, pairwise associations among perceptions, motivations, individual characteristics, and walking behaviour were examined using a series of Chi-squared tests. All 41 candidate variables were examined after having been dichotomised (variables measured on a 1–10 Likert were dichotomised as either “poor” (below 4/10) or “high” (above 6/10). The middle values (4–6) were excluded to highlight differences between lower or higher characteristics.

Secondly, machine learning was used to predict “low” or “high” walking behaviour from the variables related to perceptions, motivations, and individual characteristics. Machine learning is seen as a promising tool to address the inherent complexity of walking, related namely to a multiplicity of dimensions and variables having associations with each other (Farrahi et al., 2020), but also to the uncertainty around their relative importance (Buckley et al., 2016; Forsyth, 2015).

From the 41 variables identified as conceptually related to our question, a subset of 33 were chosen to (1) avoid redundancy or replication of information (e.g. the number of trips walked and the declared frequency of walking were seen as redundant, and declared frequency was therefore removed), and (2) omit variables that had large numbers of missing values. A gradient-boosting machine (GBM) algorithm was selected given its ability to identify patterns from a large array of variables, selecting those that are most relevant for improving prediction accuracy(Friedman, 2001). These characteristics set GBM apart from traditional methods such as logistic regression, generally incompatible with a high number of independent variables, particularly those with a high level of internal association (see results of pairwise associations below). A GBM consists of multiple decision trees which are fit sequentially, each aiming to explain the error resulting from the previous tree(Friedman, 2001).

Prior to training the model, the observations were randomly assigned to a training set (80% of the data) for model development and a test set (20% of the data) for model evaluation. Using the training set, the optimal model hyperparameters were identified. These are model parameters which must be specified before the training process. Firstly, several tree depths (1 to 5) were evaluated using the area under the receiver operating characteristic curve (AUC) metric. A depth of 2 was selected as it maximised the AUC (0.80). To avoid overfitting the model, the number of iterations (i.e. the number of trees) was dictated by a stopping criterion, found using 20-fold cross-validation (Friedman, 2001; Singh, 2018). This method automatically selects the inflection point where performance on the validation data starts to decrease while performance on the training data continues to improve. The predictive accuracy of the optimal model was then evaluated by using the model to predict walking behaviour using the 20% of data reserved for testing.

The relative importance of each variable for predicting walking behaviour was also computed during the model training process. This metric is based on the reduction in error every time a given variable is included in a tree (Friedman, 2001), and is represented on a 0–100% scale, with all variables summing to 100%. A variable with a relative importance of 30% can be interpreted as accounting for 30% of the reduction in model error, given this set of variables. As the importance of all variables adds to 100, their relative influence can be established. We observed that the use of public transport had the highest relative importance, so the modelling process was then stratified by public transport use, with separate models trained for users (n = 822) and non-users (n = 1,744) of public transport. As a last step, we fit two further models stratified by the availability of alternative travel modes (i.e. those who answered "Yes" and "No" to the question "I walk because there is no other way for me to get around"). All analyses were performed using the R software (R Core Team, 2019) and the *gbm* package was used to fit the GBM models (Greenwell, 2019). To aid reproducibility, the analysis code is provided in the supplementary file B, while the results of the tree depth optimisation for all five models (all participants, users and non-users of public transport, availability and non-availability of walking alternatives) are presented in supplementary file C.

3. Results

3.1 Pairwise associations

Multiple pairwise associations were noted between perceptions, motivations, individual characteristics, and walking behaviour. Each of the 41 variables were significantly associated with 12 to 33 other variables. Walking levels and safety at night as a barrier were both associated with 33 other variables. The chi-squared test results are presented in the Table 3 below.

Table 3: Variables examined and number of variables associated at p<.05. Full questions: see supplementary file A.

Question	**Variable examined - explanation**	**Number of variables associated, p<.05**
Q2 Travel behaviour	Levels of walking: tertile 1 or 3	33
	Did use the car in the previous week (driver or passenger)	22
Q11 Key barriers to walking in Auckland; list of items with answers y/n	**Safety, night time**	33
	Too much stuff to carry	28
	Boring routes	28
	Safety, day time	27
	Hills	26
	Weather	26
	Live too far	24
	Doesn't know how long it would take	24
	Other reason	24
	Need transport others	22
	Walking adds too much time to the journey	22
	Walking is not quick	21
	Footpaths condition	21
	Walking is too much effort	20
Q10 Key reasons for choosing to walk; list of items with answers y/n	Save money	27
	Fitness	26
	No other choice	26
	To reduce traffic congestion	26
	Walking is “me time”	26
	Contributes to address environmental concerns	25
	Allows to enjoy the weather	26
	Travel time is more consistent, when walking	24
	Less parking hassle	24
	Better walking paths are now available	22
	Save time	22
	Fun	19

	Other	15
B15 Perceived safety in relation to traffic, crime, or tripping and falling, by night time	Traffic; rated "low" or "high"*	26
	Crime; rated "low" or "high"*	27
	Tripping/falling; rated "low" or "high"*	16
S2 Age	Age 65 and over, true/false	26
B14 Perceived safety in relation to traffic, crime, or tripping and falling, by day time	Traffic; rated "low" or "high"*	20
	Crime; rated "low" or "high"*	18
	Tripping/falling; rated "low" or "high"*	12
D1 Employment	Working, studying, house duties or retired, vs not employed currently	20
D4 Level of income	Income <50,000 $ per year before tax, y/n	17

* low: <4/10; high: >6/10

The identified multicollinearity confirmed the strategy of using machine learning for modelling walking as an outcome based on diverse perceptions. The results of the test for pairwise associations were not used to select variables to be held out. As noted above, a selection of variables to be used was however performed based on redundancy of information (e.g. number of trips walked and self-declared frequency of walking) and on availability of data (excluding variables that were in large part empty because related to questions that had not been asked at every edition of the survey). The variables used for analysis are reminded in supplementary file A.

3.2 Predicting walking behaviour

The best model for predicting walking behaviour was formed using 59 trees with a maximum tree depth of 2 (AUC = 0.80). When stratified by public transport use, the performance of the models decreased for both non-users of public transport (AUC = 0.69; tree depth = 2, n trees = 45), and users of public transport (AUC = 0.61; tree depth = 1, n trees = 51). For each of these three models, the relative importance of each variable for predicting walking behaviour is shown in **Error! Reference source not found.**.

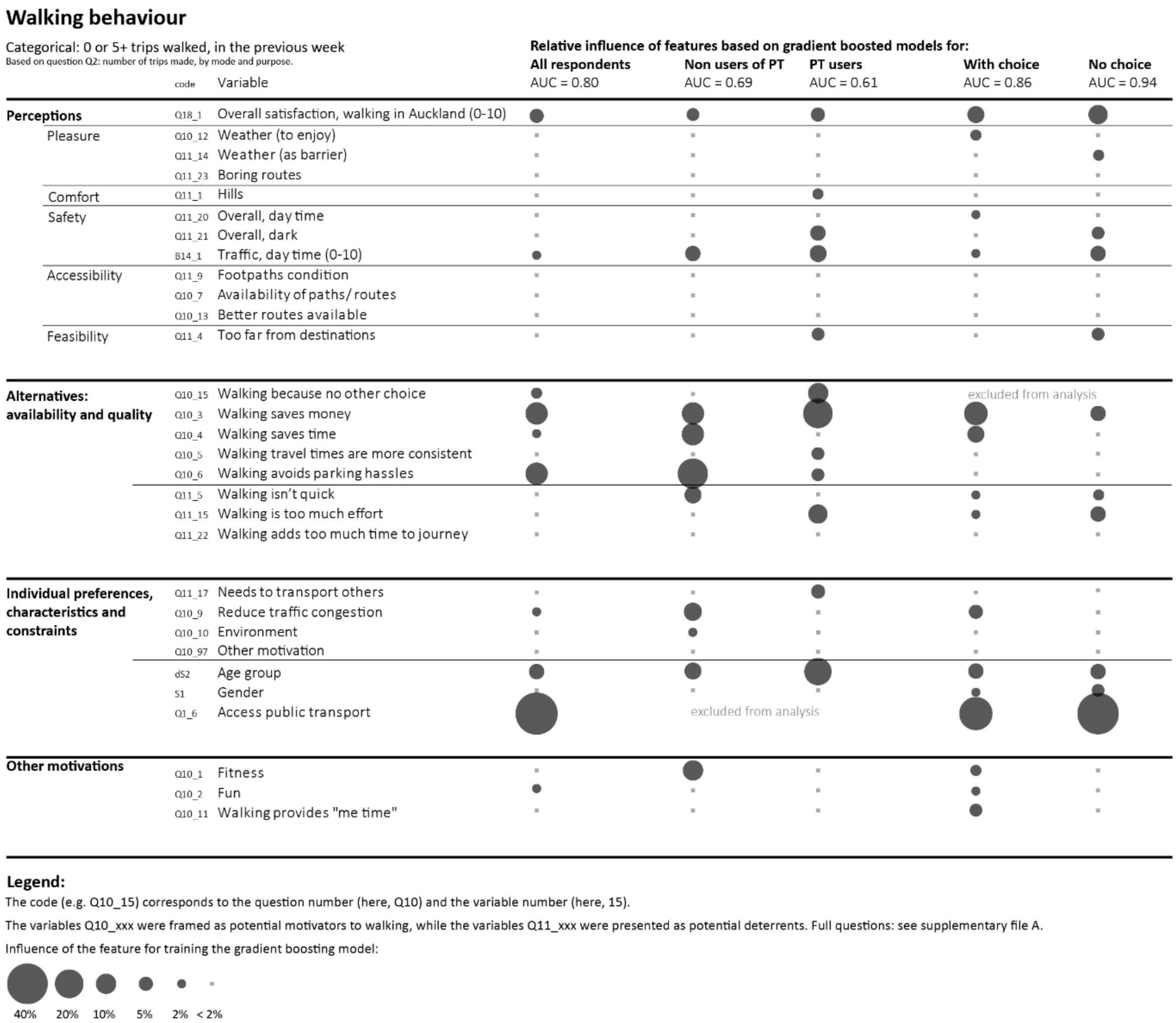

Figure 1: Relative influences of features for the whole population and the specific models for: users / non-users of public transport, and those with / without alternative modes of transport available

3.2.1 All respondents

The use of public transport in the previous week was the most important variable with 44% of the total influence. Of the people who walked 5 or more trips per week, 33% were non-users of public transport, while 77% were public transport users. The other variables displaying high importance were motivation to walk because it saves money or avoids parking hassles (both 9%), age group the motivation to help reduce traffic (both 5%), motivation to walk because it saves time (4%), and overall satisfaction with the conditions for walking and perception of safety regarding traffic (both 3.5%). Although the importance of the motivation of protecting the environment was low (1%), it was observed that the volume of walking was higher for those who care for the environment. The proportions of those motivated by the environment was higher for younger participants (17% of those aged 15-24, vs 9% for the 45-54-year olds). The importance of perceptions of the qualities of UE was below 2.5%.

3.2.2 Users and non-users of public transport

The relative importance of variables varied between users and non-users of public transport to each other, but also between both groups and the overall population. These variable importance measures must be interpreted with respect to each model's accuracy. As the AUC of these models was comparatively low, a high importance score doesn't necessarily mean that variable is a good predictor of walking behaviour. For the non-users of public transport, it can be implied that walking was compared to driving. Motivation regarding avoiding parking hassles had the highest comparative importance (22%), followed by saving money or saving time (both 12%), seeing walking as fun (10%), the perceived barrier of a less attractive travel time (7%) and the motivation to protect the environment (2%). For public transport users, motivation to walk because it saves money (21%), age group (18%), and lack of choice (10%) were the most important variables. Perceived barriers played a more important role in this group, namely too much effort (9%), safety by night (6%), the need to transport others (5%), or living too far for walking to be practical (4%).

3.2.3 Users with and without alternative travel mode options

A surprising finding was that although there were comparatively few respondents declaring not having the choice (n=337, 13% of the total sample), the model had a high accuracy (AUC=0.94) compared to the other tested models. Some notable differences were observed between the models for respondents with and without choice: public transport use had a larger importance for those "without choice" (42% vs. 26%). Further, interesting differences are noted in the relative importance of variables, when comparing those with choice and those without: motivation of reducing congestion (5% vs 0%); saving money (14% vs 6%); living too far from destinations (1% vs 4%); fun, fitness and “me time” (2 to 4% vs 0%); or perceived safety at night time (0% vs 4%). The detailed results are presented in supplementary file D.

4. Discussion

The study assessed the relative importance of users’ perceptions, motivations, and individual characteristics in relation to walking levels. Walking levels were predominantly explained by perceived qualities of walking within the transport system. Surprisingly, the importance of the perception of living too far for walking to be practical was marginal for predicting the walking levels (3.6% for PT users, 1% for non-users and 0.6% for the total population). We observed a multiplicity of associations with walking behaviour. This is consistent with recent research, showing for instance that individual characteristics are associated with both perceptions and travel behaviour (Ma & Cao, 2019). The number of relationships between perceptions is also consistent with the concept of walking environments as complex systems, with interactions between different components (e.g. traffic, carriageway width, and type of traffic controls are all related to difficulty crossing (Gehl, 2011; Speck, 2012)). Further, individual characteristics play a role given that certain features can be perceived diversely by different users (e.g. disabled or older people (Bigonnesse et al., 2018; Eisenberg et al., 2017; Mindell & Karlsen, 2012; Rosenberg et al., 2013)).

The strongest association with walking behaviour was the use of public transport, which aligns with the growing awareness of the synergies between walking and public transport use (Hillnhütter, 2016; Hutabarat Lo, 2009; National Institute for Health and Care Excellence (NICE), 2018; Speck, 2012; Van Cauwenberg et al., 2018), the potential for better synergy in cities like Auckland (Bean et al., 2008) and the need to provide efficient integrated alternatives to driving. Delivering efficient travel solutions is also crucial for populations relying on public transport and accessible environments, such as disabled people (Brennan, 2016; Burdett, 2016; Human Rights Commission, 2005; C. Smith & Dixon, 2018). Disabled people were not included in this sample and understanding their barriers of access is a key research direction. People with temporary or permanent disabilities are likely to perceive and experience more barriers in their environment (Bigonnesse et al., 2018; Eisenberg et al., 2017; Kirchner et al., 2008; Rosenberg et al., 2013; M. Smith et al., n.d.; Stafford & Baldwin, 2017).

Developing separate models for users and non-users of public transport revealed differences regarding what matters for walking and how much. Non-users of public transport implicitly compare walking to driving, putting importance on variables such as parking hassles or traffic congestion. Interestingly, the users of public transport put a higher importance on saving money than the non-users of public transport. This could relate to a difference of sensitivity to paying a ticket now as opposed to incurring sunken costs of owning a car (Kahneman, 2012), but also to a difference of socio-economic status between the two groups.

Further, important differences were noted between those declaring having/not having alternatives to walking. Those who declare having the choice implicitly compared walking with driving (e.g. noting parking hassles or putting emphasis on fitness). For those without choice, walking behaviour was closely associated with the use of public transport, suggesting walking as a “first/last mile” solution and an alternative to public transport. In the model for those without the choice, to the importance of perceived barriers was higher than in other models, while the importance of fitness and well-being factors disappeared, suggesting trips foregone if public transport is not available and walking environment not supportive.

These considerations raise the question of equity: populations living in areas with lower quality of walking environments and a poorer public transport service (e.g. car-dominated sprawl) are at risk of being car-dependent or excluded, if they cannot drive or afford to own or run a car (Ciommo & Shiftan, 2017).

Saving money or avoiding parking hassles had considerable importance in the specific models, while environmental characteristics such as footpath quality and – surprisingly - the availability of destinations (i.e. declaring not having destinations within walkable distance) did not. This last element appears as a challenge to commonly used walkability assessment tools revolving around destinations and street connectivity (e.g. Walkscore™ (Walk Score, n.d.)).

Overall, the results suggest that walking is assessed in the light of the availability of alternatives, their comparable qualities and probably the familiarity with them. This is significant as it implies that the absolute qualities of the walking environment aren't sufficient to predict behaviour.

These findings align with past research. They support the outlined Social Model of Walkability (Alfonzo, 2005; Bozovic et al., 2020; Buckley et al., 2016; Mehta, 2008) and are consistent with the existing literature outlining the role of public transport (Hillnhütter, 2016; Koschinsky et al., 2017; Rosenberg et al., 2013; Speck, 2012; Van Cauwenberg et al., 2018) and other alternatives (Rafferty et al., 2013; Sen & Kenyon, 2012; Walton & Sunseri, 2007) in the assessment of walkability. However, these aspects are inconsistently considered in walkability assessments and are formally absent from "3D" models considering density, diversity of destinations, and street connectivity. It has previously been shown that the density of destinations can be a proxy for quality and pedestrian friendliness (Koschinsky et al., 2017). Indeed, higher densities are generally found in central areas, where public transport availability and walking amenity could also be higher. Taking the view that these high level indices can be correlated with quality, the results identified here also align with the large and growing body of evidence associating "3D" types of walkability indices with walking levels (e.g. (Barnett et al., 2017; Day, 2016; Hwang, 2017)). The results of the present study contribute to the understanding of walking behaviours by simultaneously examining a wide range of perceived quality in a car-dominated environment.

The significance of findings is threefold: (1) **the Social Model of Walkability is supported** in its claim that perceptions, motivations, and individual characteristics are key explanatory factors of walking(Alfonzo, 2005; Bozovic et al., 2020; Buckley et al., 2016; Mehta, 2008); (2) **the low relative importance of the availability of destinations challenges commonly used methodologies** such as WalkScore™ (Walk Score, n.d.) (based on the availability of destinations within a certain perimeter), at least in a car-dominated realm; and (3) **the identified importance of a broader transport system (i.e. alternatives available and their qualities) prompts to develop the posited Social Model of Walkability**, adding explicitly this dimension. This is at odds with common walkability models that put emphasis on the contributions of the walking environment and often ignore the “competition” of other modes (Alfonzo, 2005; Bozovic et al., 2020; Buckley et al., 2016; Mehta, 2008).

The finding prompted revisiting the Social Model of Walkability, proposing four important new changes:

1. **The wider transport system** is now explicitly included, within the objective environmental attributes;
2. **Two new levels are integrated in the hierarchy of needs: convenience and ethics** – convenience relates to the ease of use, and had already been identified in ITDP’s recommendation for walkable cities (Institute for Transportation and Development Policy, 2018), while ethics regroups attributes such as “helps reduce traffic congestion” or “environment”;
3. **Two new dimensions are added to the hierarchy of walking needs:** (1) the relative qualities of walking, as compared with the alternatives at hand, and (2) the qualities of walking in combination with another mode – typically public transport.
4. **The availability of other modes of transport** has been re-positioned between the transport system and the hierarchy of walking needs. This is linked to the two new dimensions added to the hierarchy: only if an alternative exists, walking might be compared with this mode (e.g. to walk or to drive?) or assessed in combination (e.g. walk + bus).

Arguably, the relative importance of different dimensions could vary in different contexts (e.g. car-dominated or not) and demographics. More research is needed to better understand the importance of individual characteristics, namely disability and constraints, as well as to clarify the role of motivations and habits, possibly influencing choices (Di et al., 2017; Gärling & Axhausen, 2003; Klöckner & Friedrichsmeier, 2011; Samuelson & Zeckhauser, 1988). It should be examined for instance if individuals concerned about the environment consider the “ethics” level differently than others. This aspect should be particularly important considering societal changes, such as for instance a higher importance given to the environment and readiness to change for the younger populations (Anable, 2005).

The findings are also important for the planning practice. For the retrofit of the built environment, the results help inform the approach proposed by Stradling and colleagues (Stradling et al., 2007): identifying what matters to users, and focusing on improving those aspects first. Several important barriers that could qualify for the “first fixes” were identified. These barriers include traffic safety, overall safety at night, walking seen as too much effort, and the comparative qualities of alternatives, namely driving. Second, the findings encourage developing holistic strategies and interventions, considering walking within the transport system and the built environment, improving integration, and building positive synergies (e.g. strategic walking network taking into account public transport stops and their importance, based on patronage).

Strengths of the present study: firstly, it considered the associations between different types of perceptions and walking behaviour, which are generally overlooked in studies that directly link environmental attributes to walking. Second, the analysed data provide travel behaviour and a broad range of motivations and perceptions. Third, the analysis of the relative importance of explanatory variables on the levels of walking with machine learning allowed of examination of all the potential dimensions of interest, despite their association, so to identify which combination worked best for predicting walking levels. Arguably, the association of any one of the variables with walking would be trivial, because they all have conceptual relationships to walking as a behaviour. However, the novelty in this analysis was the holistic approach undertaken that highlighted strong effects of some variables and absence of signal for others. Fourth, the findings suggest developing the Social model of Walkability by considering explicitly (1) the relative roles of perceptions and motivations; and (2) the qualities of walking in the context of the broader transport system. Lastly, it demonstrated the application of machine learning methods for dealing with complex data, such as the multiplicity of associations between explanatory variables. Despite the potential of machine learning for exploring complex patterns, it remains underutilised when examining the associations of built environment and walking – for instance, Scopus retuned only seven results for the search for "machine learning" AND "built environment" AND walking (Deng & Yan, 2019; Ding et al., 2018; Hou et al., 2019; Naderi & Raman, 2005; Procter et al., 2018; Tao et al., 2020; Yang et al., 2019). Three of those results, all published after 2005, analysed the associations between built environment and walking behaviour (Naderi & Raman, 2005; Tao et al., 2020; Yang et al., 2019).

There are also important limitations. Firstly, the available data did not include people having difficulties walking or using a wheelchair. This population is known to be diverse and have higher barriers to access (Bigonnesse et al., 2018; Eisenberg et al., 2017; Kirchner et al., 2008; Oliver, 2013; Rosenberg et al., 2013; Stafford & Baldwin, 2017). Second, the inputs are relative to Auckland New Zealand, requiring caution before extrapolation to other environments, particularly those with different driving, public transport and built environments. Third, the format of the available data (respondents offered only yes/no answers to questions about motivations and barriers) may have prevented a more nuanced understanding of how people perceive barriers. Fourth, the distance to and quality of destinations was not considered, but they are known to affect the choice to walk and access public transport (Daniels & Mulley, 2013; Hillnhütter, 2016). Lastly, the participants declaring not walking have not been included. This was a methodological choice aimed at considering those people who are regularly exposed to their walking environment and whose perceptions of the satisfaction of their walking needs are based on a recent experience. However, considering the reasons why some people cannot or choose not to walk remains an important research topic.

5. Conclusion

The findings provide four main take-aways for both research and the practice: (1) users' perceptions of their environments need to be better understood and linked to objective aspects of the walking environment; (2) walking needs to be considered within the transport system – as a complement to public transport or an alternative to other modes; (3) it is crucial to embrace the diversity of users, examining how different constraints (e.g. having difficulties walking, seeing or hearing) might moderate the perceptions of the environment; and (4) assessing walkability should have a lower the emphasis on the pure availability of destinations, giving more room to the quality of the experience. Beyond the surveys of those who were found walking, the study of severance is key to understand what are those characteristics that can act as "deal-breakers" and prevent someone from taking a trip on foot in the first place.

6. Appendices

Supplementary file A: Questions, Auckland Transport Active Modes Survey 2018

Supplementary file B: R code

Supplementary file C: Accuracy testing

Supplementary file D: Detailed results

7. References

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